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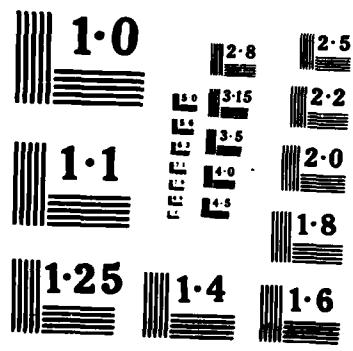
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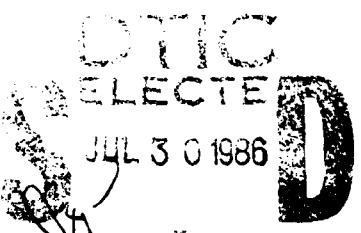
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Problems in Integrated Digital Networks

Final Report

June 13, 1986

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This final report covers work carried out under ONR Grant N00014-85-K0371. The basic problems addressed concerned the integration of diverse traffic types - e.g. voice, data, video, facsimile, etc. into a common digital network. The work fell into three areas:

1. Hybrid Multiplexing
2. Voice in Integrated Systems
3. Decentralized Optimal Flow Control

These are summarized below.

#### Hybrid Multiplexing

This work compares different multiplexing strategies at an integrated node for multibandwidth circuit-switched and packet-switched traffic. A variety of access control strategies for blocked, queued, and combined blocked/queued traffic have been studied, and results have been obtained for some novel multiserver queueing models. A paper based on this work has recently been published. [1]

The "movable boundary" strategy is a special case of this problem, with one class each of circuit-switched and packet-switched users contending for access. This strategy has been studied in detail by many investigators, including our own group. Much of this prior work was devoted to the so-called "overload" region, in which data packets experience inordinate queueing delays because of the long holding time of the circuit-switched traffic. Relatively little work has been done on analyzing the performance of the packet traffic in the normal, non-overload, region of operation. This is due to the complexity of analysis in this region. We have recently come up with new approximations for the data traffic queueing delay in this region, from

which performance figures may readily be obtained. This work appears in a new book to be published August 1986 [2].

In addition to this theoretical work, work was begun on constructing a hybrid multiplexer. This system, when completed, will enable us to provide experimental verification of the theoretical work and some of the models on which it has been based. In addition, it enables us to handle access strategies that either do not lend themselves to realistic modeling or for which analysis is too complex. It is expected that experimental results will also suggest new approaches to the theoretical work. Most of the hardware for this system has been completed and tested. Work is currently going on on developing the software for the access controller portion of the complete system.

#### Voice in Integrated Systems

A fundamental problem in the analysis and implementation of integrated services communication systems is the dissimilarity of the different services, both in their traffic characteristics and their service requirements. Voice and interactive computer data, for example, represent two extremes in traffic characteristics and service requirements. An ultimate goal of our research is to determine appropriate architectures for integrated networks, considering all levels of the network structure: the transmission medium, network interfaces, switches and multiplexers, gateways, the workstations and the user interfaces. As a tool for developing the necessary understanding, we have been studying the integration of voice with other services on a common network. The initial studies are focused on packet-switched architectures. Many arguments can be made in favor of all-packet-switched network architectures for integrated services, ranging from the economies of sharing common hardware, software and transmission facilities, to the vast potential

for new services involving such concepts as voice-computer interaction. Yet all-packet integrated architectures have not come into their own at present except, perhaps, in a few special applications. We feel that this situation can change dramatically in the next few years because of new technology. Just as the reduced cost of processing power ushered in the era of packet switching a decade ago, the availability of very wideband transmission media (e.g. optical fibers, cable, satellite), and VLSI signal processing technology should drive systems in the direction of higher degrees of multiplexing and more sophisticated forms of switching. An additional motivation for the study of all-packet systems is the fact that the distinction between "pure" packet-switched and circuit-switched systems has become blurred as these systems become more complex. Many local area network protocols are difficult to classify as either packet or circuit-switched, while new digital PBX's are just as difficult to classify. By studying integration from the "packet" viewpoint, we expect eventually to evolve toward ideas which will probably be "unclassifiable" in present terms.

Packet voice has been studied extensively for almost as long as packet switched networks have been in existence. A good historical review appears in [3]. Several packet voice experiments on distributed networks [4] satellite networks [5] packet radio networks [6] and local area networks [7] have been undertaken. In addition, performance has been studied through simulation [8] and analysis ([9], [10]). Our objective in this research is to move beyond existing voice network designs and protocols. By using packet voice as a prototypical case study in integration, we hope to determine what architectures are best for the integration of still more diverse services: data, facsimile, file transfer, graphics and video. The work to date has both an analytical and experimental component. On the theoretical side, using a mathematical model that captured the essential features of a packet

voice/data multiplexer, we were able to determine the tradeoffs among packet loss, reconstructed voice delay, and channel capacity. A doctoral thesis has reported this work. [11] Furthermore, to align our theoretical results with subjective voice quality criteria we constructed a real time packet voice simulator (implemented on our Masscomp computer), which simulates all of the operations in a packet voice system, including impairments such as queueing delays and packet loss. The resultant voice quality can be monitored by a listener for performance comparisons. On the experimental side, we are in the early stages of defining the architecture of a multimedia workstation capable of providing integrated communications in real time via voice, data, images and video. Hardware and software development of the voice and video interfaces is now underway.

#### Decentralized Optimal Flow Control

In [12] the problem of network and user flow control arising in local area networks and time sharing computer systems was defined and investigated. A multiclass queueing system with two classes of users served as a model for which optimal flow control strategies were to be derived. The first class models the interfering traffic while the second class models the traffic generated by a new user logging onto the network. Decentralized optimal flow control strategies were obtained that maximize the network (respectively user) time delay constraint. These strategies use partial observations: only the number of the second class of packets is available for controlling the packet flow. Two structural results were identified. The first is a representation theorem, which shows that the conditional arrival rate estimate is a sufficient statistic for the network optimization problem. The second result, referred to as the separation principle, provides a solution to the user

optimization problem via the conditional departure rate estimate. Under both optimization criteria, the resulting optimal control was shown to be a window-type flow control mechanism (bang-bang control). The window size  $L$  is a function of the maximum tolerated time delay  $T$ , the input capacity  $c$ , the service rate  $u$  and the interfering packet flow . It was also shown that the optimal window size under the network criterion is smaller than or equal to that under the user criterion.

By constructing the equivalent arrival and departure processes, our analysis showed that the Norton equivalent is simply the conditional estimate of the arrival and departure rates. The original work by Chandy, et. al. (1975) on Norton's equivalent for queuing networks [13] has aroused a lot of interest in parametric studies and aggregation methods for queueing systems. Various authors have since extended the results to more general multi-class queuing networks [14], [15], [16]. In these investigations, the interpretation of the Norton's equivalent has drawn analogy from circuit theory; the aggregation procedure is the "shorting" of a subsystem or subnetwork, then obtaining the throughput of this "shorted" subsystem. While this interpretation provides a physically intuitive understanding for the designers and analysts of computer communication networks, it does not reveal the mathematical structure of the aggregation procedure. The fact that these results hold only for "product form" networks points out the limitation of this physical interpretation. Since the queueing models adopted for analysis and performance evaluation of computer communication networks are based on stochastic models, it would only be natural to provide a probabilistic interpretation of the Norton's equivalent.

Recently, Brandwajn [17] proposed a framework for evaluating approximation techniques employed in the analysis of queueing systems. This

framework consists of two steps. Equivalence, the first step, is merely obtaining state equations for a suitably chosen marginal probability, and, as such, is an exact transformation regardless of whether the system is nearly completely decomposable or possesses a product-form solution. The second step, decomposition, is the computation of conditional probabilities introduced through equivalence.

In [18] we presented a general framework for obtaining the equivalent state description for general Markovian queueing networks. While the results in [17] concern mainly approximation techniques, our motivation stems from optimal flow control problems in computer communication networks [19], [20], [12], [21]. In such problems, the idea of Norton's equivalent in the sense of an exact transformation is needed in proving structural results such as separation theorems. We have shown that the Norton's equivalent is indeed a very fundamental entity in probability theory, namely, a conditional expectation. In so doing, we based our derivations on general techniques developed in a measure theoretical setting in [22]. Under such a framework, the Norton's equivalent can be given much more generality than is possible with the physical interpretation mentioned above.

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Degrees Awarded

S. Ganguly, Ph. D.

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Papers Presented or submitted for publication

1. B. Kraimeche and M. Schwartz, "Analysis of Traffic Control Strategies in Integrated Services Networks," IEEE Trans. on Comm., Oct. 1985.
2. S. Ganguly, "Analysis and Performance Evaluation of a Packet Voice," (submitted for publication).
3. A. A. Lazar and M. T. Hsiao, "Network and User Optimal Flow Control with Decentralized Information," (submitted for publication).
4. M. Luhanga and T. E. Stern, "Analytical Modeling of Small Packet Voice Systems," Int. J. Elect. Engng Educ. Vol. 22 pp. 339-344.

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